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Colour- and Form-dependent Loss of Plastic Micro-debris from the North Pacific Ocean

DAVID G. SHAW AND ROBERT H. DAY*
Institute of Marine Science, University of Alaska, Fairbanks, AK 99775-1080, USA
*Present Address: Alaska Biological Research, Inc., P.O. Box 81934, Fairbanks, AK 99708 USA

Floating plastic was collected with a neuston sampler at 27 locations in the North Pacific Ocean in 1987 and 1988. The plastic particles obtained were sorted according to size, physical form (e.g. pellet, line, fragment), and colour. Comparison of the size distribution of plastic observed with that predicted by a simple physical fragmentation model indicated that some forms, colours, and size fractions were significantly under-represented. We consider four possible explanations of these results and conclude that it is likely that marine organisms selectively remove plastic particles whose size, shape, and colour allow them to be mistaken for prey items. We further conclude that ingestion of small plastic objects by marine organisms occurs in substantial quantities.

The accumulation of floating plastic in the oceans has been observed and recorded in the scientific literature for at least two decades (Carpenter & Smith, 1972; Venrick *et al.*, 1973). The proceedings of three symposia (Shomura & Yoshida, 1985; Wolfe, 1987; Shomura & Godfrey, 1990) provide an introduction to the now extensive literature on the abundance of plastic and other marine debris at sea and on shorelines, as well as on the impacts of these materials on ocean life.

Plastic enters the ocean in runoff from the land, by intentional dumping of trash by ships at sea, and from accidental loss of fishing gear and other plastic objects from ships. Floating plastic debris includes a variety of large and small plastic objects manufactured for industrial and consumer uses as well as pellets of unfabricated plastic resin. The lifetimes of plastics at sea are not known but generally are thought to range from years to decades, depending on the physical and chemical form of the object (Gregory, 1978). Plastics at sea become brittle and undergo mechanical fragmentation, presumably leading to microscopic particles of plastic 'dust' (Gregory, 1978). In 1989, an international agreement (MARPOL 73/78 Annex V) prohibited discharge of plastic objects from ships at sea (Pearce, 1992). Thus, there is reason for some optimism that the abundance of plastic in the oceans will gradually diminish, as did the amount of floating tar following the adoption of similar international agreements in the 1970s that prohibited the routine discharge of waste oil at sea (National Research Council, 1985).

Plastics at sea are known to have adverse impacts on marine organisms, although the extent of such problems is difficult to quantify (e.g. see Shomura & Yoshida, 1985; Wolfe, 1987; and Shomura & Godfrey, 1990). Large plastic objects, especially lost and discarded fishing nets, often cause mortality of fishes, turtles, and marine mammals by entanglement. Small objects have been found in the stomachs of fish, birds, and other marine organisms, sometimes in sufficient quantities to obstruct the gut.

In this report, we describe the influence of size and colour on the abundance of small pieces of plastic in the North Pacific. In collaboration with a colleague, we previously described (Day *et al.*, 1990) the geographic distribution of the plastic whose size distribution is reported here.

Materials and Methods

Samples were collected at 27 locations in the North Pacific Ocean during July to November 1987 and July 1988 with a Sameoto neuston sampler (Sameoto & Jaroszynski, 1969) fitted with a net of mesh-size 0.053 mm. At each location, the sampler was towed horizontally at the ocean surface off the side of the ship at a known speed (usually 2.5–3.5 kt) for 10 min. Following Day *et al.* (1990), the time that the mouth of the net was not at the surface (to the nearest 15 sec) was subtracted from the 10-min sampling period. The area of ocean surface sampled was calculated by multiplying the length of surface water sampled (corrected fishing time multiplied by ship's speed) by the width of the net opening (0.5 m; see Day *et al.* 1990). Samples were washed into plastic bottles that had been scrubbed carefully inside, and 10% formalin was added to preserve living tissue.

Samples first were treated in the laboratory with rose bengal, which stains biological tissue and thus makes it easier to distinguish plastic, then were rinsed through

Tyler sieves of five mesh-sizes: 1.000 mm, 0.710 mm, 0.500 mm, 0.250 mm, and 0.053 mm. Sieved samples were washed into individual sorting trays for sorting and identification under a light microscope. Individual pieces of plastic were counted and sorted into standardized categories of form and colour. Categories of form included polyethyelene pellet, polyethylene fragment, styrofoam (expanded polystyrene) fragment, polypropylene line fragment, miscellaneous or unidentified line fragment, and miscellaneous or unidentified plastic. Categories of colour included black/grey, blue, brown, green, orange, red/pink, tan, transparent, white, yellow, and miscellaneous or unidentified, following Day *et al.* (1990).

For each sampling location, the number of plastic particles of each form and colour was tallied for each size-class. The area of ocean surface sampled was used to convert the tallies to estimates of density (number of particles km^{-2}). In addition, the number of each form and colour of plastic in the different size-classes was tallied as a frequency and was converted to a percentage of the total number of particles in each size-class. Because the widths of the size-classes were not uniform, the density for each size-class was divided by the width of that size-class, in mm, to make densities comparable as number of objects km^{-2} of sampling area mm^{-1} of size-class interval (i.e. 'normalized densities'). For this computation, the upper limit for the size-class 1.000^{+} mm was considered to be 10 mm.

A Friedman test (Conover, 1980; Zar, 1984) was used to test the hypotheses that the total normalized density of plastic and densities of individual forms of plastic did not differ significantly among size-classes; test results were corrected for tied ranks. Multiple comparisons (Conover, 1980) were used to identify significant differences between size-classes in the test results. Because the size-class data from each sample were not independent, the Friedman test was more appropriate than a Kruskal-Wallis test (Conover, 1980). The hypothesis that the relative abundance of each colour did not change with size was tested with a Chi-square contingency table (Zar, 1984), using the compiled data on frequencies of the various colours of plastic by size-class. When significant differences were found, cells were inspected for their individual contributions to the total Chi-square value.

Results

Size characteristics

Plastic was found in all of the size-classes at 11 (40.7%) of the 27 sampling locations. Plastic was recorded in 0.500 mm size-class the most frequently (22 locations; 81.5%), followed in decreasing order of occurrence by size-classes 0.250 mm (21 locations; 77.8%), 1.000 mm and 0.710 mm (each at 20 locations; 74.1%), and 0.053 mm (19 locations; 70.4%).

The total normalized density of plastic differed significantly among size-classes ($\chi^2=29.648$; df=4; $p<0.05$), with the pattern being: 0.500 mm=0.250 mm=0.053 mm > 0.710 mm > 1.000^{+} mm. Means and standard deviations of normalized densities, in decreasing size, were: 3000 ± 4300 pieces km^{-2}; 36 500 ± 54 300 pieces km^{-2}; 83 800 ± 111 500 pieces km^{-2}; 150 600 ± 251 100 pieces km^{-2}; and 115 900 ± 247 100 pieces km^{-2} (the top curve [diamonds] in Fig. 1).

Colours and abundance of plastic

Transparent particles were most common (49.0% of all particles), followed by white (25.2%), blue (16.9%), and black/grey (5.2%). The six other colour categories (brown, 0.1%; green, 1.8%; orange, 0.0%; red/pink, 0.1%; tan, 1.0%; and yellow, 0.5%) together accounted for only 3.5% of all plastic objects. Because many of the cells in a preliminary Chi-square test of all of the frequency data contained expected values less than 5 (most with expected values near or less than 1, thereby invalidating the overall Chi-square test), data for all colours except black/grey, blue, transparent, and white were excluded from further analysis. Colour frequency was not independent of size-class in the reduced data set ($\chi^2=130.28$; df=12; n=791; $p<0.05$). The colours black/grey, blue, transparent, and white contributed 8.26 (6.3%), 35.58 (27.3%), 11.94 (9.2%), and 74.50 (57.2%), respectively, to the total Chi-square value.

The normalized density of total plastic and of the four most abundant colour categories generally increased with decreasing size, except in the smallest size-class (Fig. 1). Blue plastic constituted an increasing proportion of successively smaller size-clases, from 6.1% in the largest to 30.3% in the smallest (Fig. 2). The abundance of transparent plastic generally paralleled that of blue plastic, in that it increased steadily in frequency in all but the smallest size-class. In contrast, white plastic consistently decreased in abundance in successively smaller size-classes, from 45.9% in the largest to 8.3% in the smallest. The abundance of black/grey plastic showed no consistent trend by size-class.

Form and abundance of plastic

Fragments form by breakage of larger pieces of plastic; their main identifying characteristics are irregular shapes and rough, broken edges. Fragments were the most abundant of the plastic forms (Figs 3 and 4), being recorded at 25 (92.6%) of the 28 locations. The normalized density of fragments was significantly higher for the smaller size-classes ($\chi^2=25.130$; df=4; $p<0.05$), with the pattern being: 0.500 mm=0.250 mm=0.053 mm > 0.710 mm > 1.000^{+} mm.

Plastic objects which were soft, opaque, and white or nearly white were classified as sytrofoam (expanded polystyrene); both fragments and unbroken objects were included. Styrofoam was uncommon, being recorded at only four sampling locations (14.8%). The normalized density of styrofoam did not differ significantly among size classes ($\chi^2=0.845$; df=4; $p>0.05$).

Polypropylene line fragments primarily included small fibres of larger pieces of polypropylene line, which is commonly used on ships; they were coloured and buoyant. Polypropylene line fragments were uncommon, being recorded at only five locations (18.5%). The normalized density of polypropylene

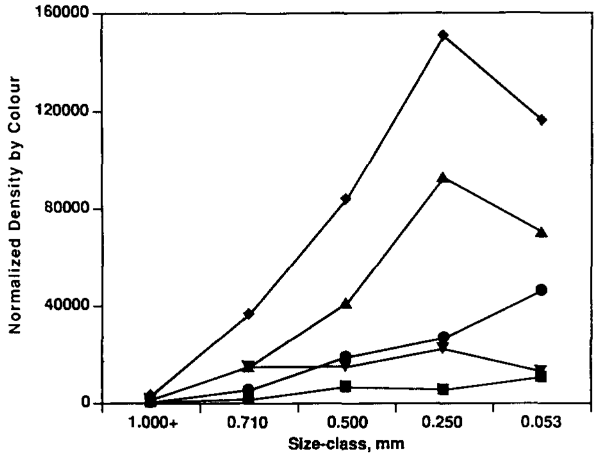

Fig. 1 Normalized density (number of objects km^{-2} of sampling area mm^{-1} of size-class interval) of plastic at 27 locations in the North Pacific Ocean by size-class (mm) as a function of colour (◆, total; ▲, transparent; ●, blue; ▼, white; ■, black/grey).

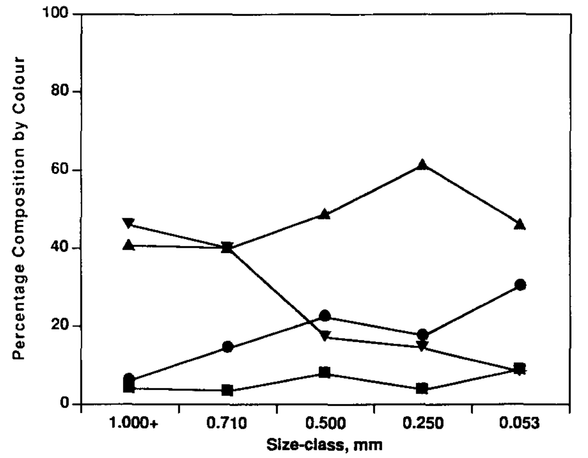

Fig. 2 Percentage distribution of plastic at 27 locations in the North Pacific Ocean by size-class (mm) as a function of colour (▲, transparent; ●, blue; ▼, white; ■, black/grey).

line fragments differed significantly among size classes ($\chi^2=10.786$; df=4; $p<0.05$), with the pattern being: 1.000$^+$ mm>0.500 mm>0.710 mm=0.250 mm=0.053 mm. These differences probably resulted from the fact that the fragments consisted either of multiple threads woven into a piece of line or of individual threads from a piece of line; hence, they were found in only a few size-classes.

Miscellaneous lines/threads are small fragments of larger lines; this category includes monofilament line fragments and fragments of woven line that did not appear to be polypropylene (i.e. were not buoyant in the fresh water used for sorting). Miscellaneous lines/threads were common, being recorded at 22 locations (81.5%). The normalized density of miscellaneous lines/threads did not differ significantly among the size-classes ($\chi^2=8.366$; df=4; $p>0.05$).

Pellets (cylindrical pieces of plastic often shipped from resin manufacturers to plastic fabricators) and unidentified plastic were the two least abundant plastic types overall, each being recorded at only one location (3.7%). The normalized density of neither pellets nor unidentified plastic differed significantly among size-classes ($\chi^2=4.000$; df=4; $p>0.05$); results for these forms are not plotted in Figs 3 and 4.

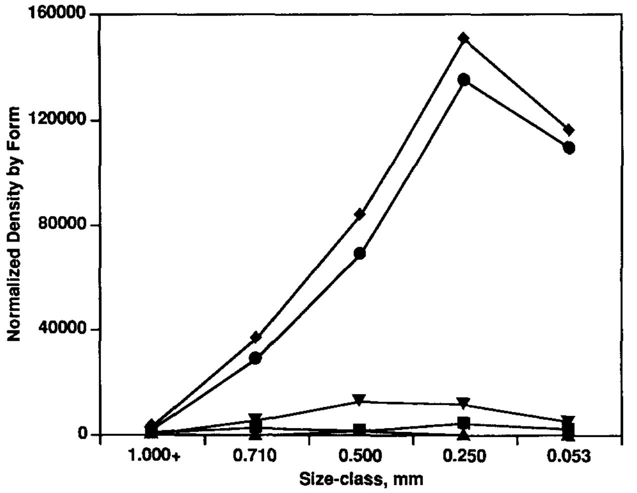

Fig. 3 Normalized density (number of objects km^{-2} of sampling area mm^{-1} of size-class interval) of plastic at 27 locations in the North Pacific Ocean by size-class (mm) as a function of form (◆, total; ●, fragment; ■, styrofoam; ▲, polypropylene line; ▼, miscellaneous line and threads).

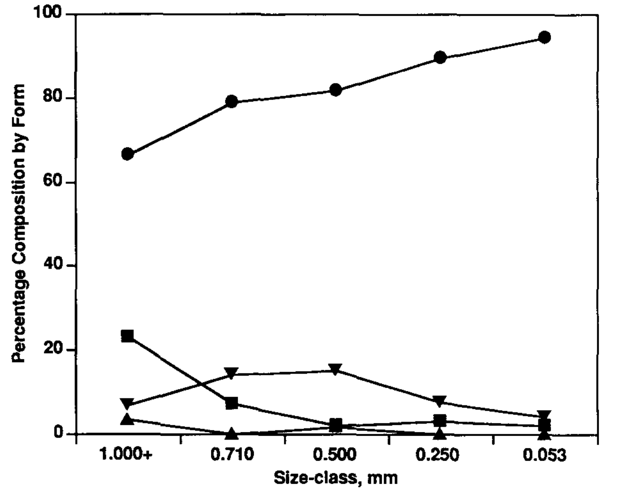

Fig. 4 Percentage distribution of plastic at 27 locations in the North Pacific Ocean by size-class (mm) as a function of form (●, fragment; ■, styrofoam; ▲, polypropylene line; ▼, miscellaneous line and threads).

Discussion

Our results show that most small (0.05–10 mm) plastic objects in the North Pacific Ocean in the mid 1980s were fragments of larger objects, similar to the findings reported by Day *et al.* (1985, 1990) and Day & Shaw (1987). Although direct data are lacking, it seems reasonable to us that at least some, and probably most, of the fragmentation that produces these objects occurs at sea. Based on the assumption that the rate of input of plastics to the ocean was not changing rapidly at the time these data were collected, it is probable that a steady-state distribution of size-classes of plastic fragments exist at sea. Each plastic object entering the ocean gradually fragments to give progressively larger numbers of smaller particles until these fragments are removed by stranding, loss of buoyancy, ingestion by marine animals, or other processes. For example, estimated numbers from a 10×10 mm piece of plastic broken into the midpoints of our five size-classes without loss of pieces would be 3, 137, 273, 711, and 4328 pieces, respectively (ratios of normalized densities would be 1: 45.7:91.0:237.0:1442.7). Our data for normalized plastic densities (top curves in Figs 1 and 3) show an increase in particle abundance with decreasing size (except for the smallest size-class), but this increase does not follow the hypothesized ratios and, more importantly, varied with colour and form.

There are four possible explanations for the results that we observed: *1.* potential biases of the sampling method relative to size and colour distributions; *2.* differences in fragmentation rates of plastics of different colours or forms; *3.* the effects of residence time and initial size distribution on the steady-state size distribution; and *4.* biological factors that affect the distribution of fragment sizes. Although we did not test explicitly any of these four possible explanations, we believe that we can provide insights into the probability of each of these explanations.

Potential biases of the sampling method involved different abilities to sort plastic of different colours. We cannot exclude the possibility that the plotted decrease in normalized density for the smallest size-class is due to human error in the sorting process. It is possible that light plastics were more difficult to identify in the smaller size-classes than were the other colours such as blue, resulting in the light plastic's composing progressively smaller percentages of the total plastic in progressively smaller size-classes. However, because we were aware of this potential bias, we were extremely careful in sorting these smaller particles. Further, staining of biological tissue with rose bengal stained the light-coloured zooplankters (which could be confused with light plastic), strongly decreasing the magnitude of this potential bias. We do not believe that other sampling biases could result in the observed size and colour distributions.

The chemical and physical processes that cause plastic decomposition are known, but their quantitative aspects in the ocean appear to be poorly understood. In the presence of sunlight, all plastics undergo chemical reactions in which polymer molecules are crosslinked, causing embrittlement and reducing the physical stress needed for fragmentation (van Krevelen, 1972). However, fragmentation rates are unknown and probably vary greatly with environmental factors that affect light intensity, such as latitude and average regional cloud cover. Plastic composition also affects fragmentation rates because, depending on the plastic's intended use, additives may be used either to accelerate or retard photodecomposition and because of variations in the use of plasticizing agents whose leaching also promotes embrittlement. When stranded on beaches, darker coloured plastic objects would be expected to absorb more sunlight. The resulting increase in temperature might lead to more rapid decomposition. However, at sea, all colours of plastic will be at the seawater temperature and decomposition rates will not vary with colour due to differential heating.

While many aspects of plastic decomposition in the marine environment are uncertain, most observers estimate that the residence time of pelagic plastics is on the order of years to decades. For example, Gregory (1978) estimated that it would take 3–50 yr for complete degradation of plastic on beaches and much longer at sea. Residence time and initial size distribution may affect the size distribution of plastic found at sea but probably have little effect on colour distribution. For example, a small piece of plastic could decompose at sea more quickly than could a large piece. If the initial size distribution includes only small particles, the resulting size distribution will include only small particles, whether the residence time is short or long. If the initial size distribution includes only large particles and the residence time is short, the resulting size distribution will include only large particles. If, however, the initial size distribution includes large particles and the residence time is long, the resulting size distribution may include a diversity of sizes, as we observed. Although this is a plausible explanation for the observed results, we doubt its importance, primarily because residence time could have no effect on colour distribution, as we observed.

Plastics of different colours clearly exhibited different relative abundances among size-classes. The relative abundance of blue plastic within each size-class increased with decreasing size, whereas white plastic decreased in relative abundance with decreasing size. Although the trends for transparent and for grey/black objects were less pronounced, these colours also appeared to increase with decreasing size. As discussed above, we are not aware of any simple physical mechanism which could account for the selective loss of white plastic in these smaller size-classes from the surface of the ocean. In our opinion, a more probable explanation is that marine organisms feeding at the surface tend to mistake white (and other light-coloured) plastic objects smaller than 0.5 mm for food items and remove them by ingestion. While ingestion does not permanently remove plastics from the marine environment, this process can selectively decrease the numbers of plastics of some colours which can be sampled by a neuston net (as in this study) at any given point in time.

The lack of a pronounced pattern in size distribution as a function of form in Fig. 4 may mean that organisms which ingest plastic do not discriminate on the basis of form. Alternatively, it may mean that our categories of form are not those by which discrimination is made. We classified most plastics in all size-classes as fragments. It may be that, within this category, some shapes are more attractive than others to organisms that consume plastic objects.

We can do little more than speculate about which species may be removing plastic from the North Pacific. Food-habits studies of zooplankton have recorded plastic only once (*Sagitta elegans*; Carpenter *et al.*, 1972). However, this scarcity of reports may reflect lack of recognition of plastics by observers, rather than the absence of plastic. Those groups most probably ingesting decomposed plastic are larval and juvenile fish and squids. Both are active predators that forage using visual cues and frequently prey on small zooplankton (e.g. Hart, 1973), behaviour that would result in the ingestion of those colours of plastic that resemble the most abundant potential prey organisms (i.e. white, tan, and yellow). Plastic has been found in stomach contents of adult flying squids (Araya, 1983; Day, unpubl. data) and larval and juvenile fish (e.g. Carpenter *et al.*, 1972, Colton *et al.*, 1974, Hoss & Settle, 1990), which have been found to ingest only white, opaque polystyrene spherules and to avoid transparent spherules (Carpenter *et al.*, 1972). In contrast, Colton *et al.* (1974) found that fish ingested little plastic (although it was unclear what the normal feeding depths and the normal species of prey of any of those fish were). Plastic also has been found in the stomachs of a wide range of sea turtles (Balazs 1985) and seabirds (e.g. Day *et al.*, 1985; Ryan, 1987, 1988; Moser & Lee, 1992; and numerous papers in Shomura & Godfrey, 1990) from around the world, with strong evidence for selective ingestion of plastic of some colours by seabirds (e.g. see Day *et al.*, 1985; Moser & Lee, 1992).

The results presented here show the size distributions of plastics from the North Pacific Ocean vary with colour. We strongly doubt that this is an observational artifact and are aware of no simple physical or chemical explanation. We conclude that published observations of plastic ingestion by a wide range of marine organisms, taken with the colour-dependent size distribution that we report here, combine to make a strong case that ingestion of small plastic objects by marine organisms occurs in substantial quantities. It remains to be determined what, if any, ecological consequences result from this ingestion.

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Araya, H. (1983). Fishery, biology, and stock assessment of *Ommastrephes bartrami* in the North Pacific Ocean. *Mem. Nat. Mus. Victoria* **44**, 269–283.

Balazs, G. H. (1985). Impact of ocean debris on marine turtles: entanglement and ingestion. In *Proceedings of the Workshop on the Fate and Impact of Marine Debris* (R. S. Shomura & H. O. Yoshida, eds), pp. 387–429. U.S. Dep. Commer., NOAA Tech. Memo. NMFS, NOAA-TM-NMFS-SWFC-54.

Carpenter, E. J. & K. L. Smith, Jr. (1972). Plastics on the Sargasso Sea surface. *Science* **175**, 1240–1241.

Carpenter, E. J., Anderson, S. J., Harvey, G. R., Miklas, H. P. & Peck, B. B. (1972). Polystyrene spherules in coastal waters. *Science* **178**, 749–750.

Colton, J. B., Jr., Knapp, F. D. & Burns, B. R. (1974). Plastic particles in surface waters of the northwestern Atlantic. *Science* **185**, 491–497.

Conover, W. J. (1980). *Practical Nonparametric Statistics*, 2nd ed. Wiley, New York.

Day, R. H. & Shaw, D. G. (1987). Patterns in the abundance of pelagic plastic and tar in the North Pacific Ocean, 1976–1985. *Mar. Pollut. Bull.* **18**, 311–316.

Day, R. H., Shaw, D. G. & Ignell, S. E. (1990). The quantitative distribution and characteristics of neuston plastic in the North Pacific Ocean, 1985–1988, In *Proceedings of the Second International Conference on Marine Debris, 2–7 April 1989, Honolulu, Hawaii* (R. S. Shomura & M. L. Godfrey, eds), pp. 247–266. U.S. Dep. Commer., NOAA Tech. Memo. NMFS, NOAA-TM-NMFS-SWFC-154.

Day, R. H., Wehle, D. H. S. & Coleman, F. C. (1985). Ingestion of plastic pollutants by marine birds. In *Proceedings of the Workshop on the Fate and Impact of Marine Debris* (R. S. Shomura & H. O. Yoshida, eds), pp. 344–385. U.S. Dep. Commer., NOAA Tech. Memo. NMFS, NOAA-TM-NMFS-SWFC-54.

Gregory, M. R. (1978). Accumulation and distribution of virgin plastic granules on New Zealand beaches. *N.Z. J. Mar. Freshwat. Res.* **12**, 399–414.

Hart, J. L. (1973). Pacific fishes of Canada. *Fish. Res. Board. Can. Bull.* **180**.

Hoss, D. E. & Settle, L. R. (1990). Ingestion of plastic by teleost fishes. In *Proceedings of the Second International Conference on Marine Debris, 2–7 April 1989, Honolulu, Hawaii* (R. S. Shomura & M. L. Godrey, eds), pp. 693–709. U.S. Dep. Commer., NOAA Tech. Memo. NMFS, NOAA-TM-NMFS-SWFC-154.

Moser, M. L. & Lee, D. S. (1992). A fourteen-year survey of plastic ingestion by western North Atlantic seabirds. *Colon. Waterbirds* **15**, 83–94.

National Research Council (1985). *Oil on the Sea: Input, Fate and Effects*. National Academy Press, Washington, DC 601 pp.

Pearce, J. B. (1992). Marine vessel debris: a North American perspective. *Mar. Pollut. Bull.* **24**, 586–592.

Ryan, P. G. (1987). The incidence and characteristics of plastic particles ingested by seabirds. *Mar. Environ. Res.* **23**, 175–206.

Ryan, P. G. (1988). Intraspecific variation in plastic ingestion and the flux of plastic through seabird populations. *Condor* **90**, 446–452.

Sameoto, D. D. & L. O. Jaroszynski (1969). Otter surface sampler: a new neuston net. *J. Fish. Res. Board Can.* **25**, 2240–2244.

Shomura, R. S. & Godfrey, M. L. (eds). (1990). *Proceedings of the Second International Conference on Marine Debris, 2–7 April 1989, Honolulu, Hawaii.* U.S. Dep. Commer., NOAA Tech. Memo. NMFS, NOAA-TM-NMFS-SWFC-154.

Shomura, R. S. & Yoshida, H. O. (eds). (1985). *Proceedings of the Workshop on the Fate and Impact of Marine Debris.* U.S. Dep. Commer., NOAA Tech. Memo. NMFS, NOAA-TM-NMFS-SWFC-54.

van Krevelen, D. W. (1972). *Properties of Polymers: Correlations with Chemical Structure.* Elsevier, Amsterdam.

Venrick, E. L., Backman, T. W., Bartram, W. C., Platt, C. J., Thornhill, M. S. & Yates, R. E. (1973). Man-made objects on the surface of the central North Pacific Ocean. *Nature (London)* **241**, 271.

Wolfe, D. A. (ed.) (1987). Plastics in the sea: selected papers from the Sixth International Ocean Disposal Symposium. *Mar. Pollut. Bull.* **18 (6B)**, 301–365.

Zar, J. H. (1984). *Biostatistical Analysis*, 2nd ed. Prentice-Hall, Englewood Cliffs, New Jersey.